3u4

THEORETICAL AND EXPERIMENTAL STUDIES OF SPACE-RELATED PLASMA WAVE PROPAGATION AND RESONANCE PHENOMENA

Semiannual Report No. 15

NASA Research Grant NGL 05-020-176

SU-IPR Report No. 580

July 1974

(NASA-CR-139275) THEORETICAL AND EXPERIMENTAL STUDIES OF SPACE-RELATED PLASMA WAVE PROPAGATION AND RESONANCE PHENOMENA Semiannual Report, 1 Jan. - (Stanford Univ.) 25 p HC $4.25 CSCL 20I N74-30162 Unclas G3/25 54857

Institute for Plasma Research
Stanford University
Stanford, California 94305

STAFF

NASA Research Grant NGL 05-020-176

for the period

1 January - 30 June, 1974

SENIOR STAFF

Prof. F. W. Crawford (Part-time)
(Principal Investigator)

Dr. K. J. Harker (Part-time)

Dr. D. B. Ilić (Part-time)

Dr. H. Kim (Part-time)

Dr. Y. Y. Kuo (Part-time)

PART-TIME RESEARCH ASSISTANTS

J. A. Edighoffer	Y. M. Peng
Y. Matsuda	D. M. Sears
R. R. Myers	R. J. Vidmar

FOREWORD

The subject of NASA Research Grant NGL 05-020-176 is the theoretical and experimental study in the laboratory of space-related plasma wave propagation and resonance phenomena. Research supported by the grant has been proceeding under the direction of Prof. F. W. Crawford since its inception on 1 December 1966. This is the fifteenth semiannual report, and covers the period from 1 January to 30 June, 1974.

CONTENTS

I. INTRODUCTION

The research to be discussed in this semiannual report is concerned primarily with plasma wave and resonance phenomena observable in the ionosphere. Much of our previous work under the grant has involved direct laboratory simulation of puzzling effects occurring in space plasmas. Such projects led to better understanding of "Alouette" resonances, the resonance probe, some aspects of whistler propagation and triggered VLF emissions, and contributed to the development of a variety of new plasma diagnostic techniques. During this period, knowledge of plasma wave and resonance phenomena, in both the linear and nonlinear régimes, has advanced rapidly as a result of considerable study world-wide of space and laboratory plasmas, and the puzzling phenomena are now fewer. It is possible to plan experiments with far more confidence in the theoretical predictions than we could only three to five years ago. The motivation and aims of our research program have consequently progressed with these advances, and bring us naturally to the projects to be discussed in Sections II and III, particularly in relation to the NASA Space Shuttle Program.

The Shuttle Program offers exciting new possibilities for plasma physics experimentation. Although its realization may not occur until about 1980, a Plasma Physics and Environmental Perturbation Laboratory (PPEPL) is expected to form part of the program, and is already in the planning stages: the Principal Investigator for this grant is a member of the newly-formed Atmospheric, Magnetospheric, and Plasmas-in-Space (AMPS) Science Working Group. If the PPEPL enterprise is to be successful, a new generation of space plasma experiments should be proposed and submitted to critical scrutiny for scientific merit and experimental feasibility. To be attractive, they should profit from the unique plasma environment and parameter ranges accessible to the PPEPL to perform basic plasma experiments not feasible in the laboratory, or to greatly improve others by virtue of the large volumes of essentially fully-ionized plasma available for study; they should provide refined diagnostics for plasma conditions local to the vehicle, and they should develop new techniques for improving understanding of the ionosphere itself by nonlocal probing, e.g. with electron beams or waves.

Over the last eighteen months or so, six Ph.D. theses have been completed with support from the grant. This has given us the opportunity to phase out a number of projects, and to initiate others of more direct relevance to the PPEPL. Although this report is primarily concerned with work carried out during the reporting period, 1 January - 30 June, 1974, for completeness we shall review the entire year's program, and its relation to these earlier projects.

II. CURRENT RESEARCH PROGRAM

We shall describe briefly here those projects that have been active during the last twelve months. Many of them are essentially completed. Others will be continued during the coming year. Proposed extensions to them, and new projects will be discussed briefly in Section III. A bibliography of Reports, Conference Papers, and Publications resulting from the grant since 1 July 1973 is given in Section IV.

A. Whistlers

We have been studying various aspects of whistler propagation over a period of several years, beginning with laboratory measurements of whistler dispersion characteristics in a cold collisional plasma,[21,22*] continuing with numerical studies of small-signal whistler instabilities, for propagation both parallel[23,24] and oblique[25] to the earth's magnetic field in nonthermal plasmas, and finally extending this work to the nonlinear phenomena associated with triggered VLF emissions[9,26,27] modulational instabilities,[28] and Alfvén wave excitation.[8,12] During the past year, we have also studied excitation of VLF waves by electron beams, and ULF waves by metallic electric and magnetic dipole antennas. Progress in the active areas is as follows:

Triggered VLF Emissions: Apart from a conference presentation,[9] no further contributions have been made in this area during the past year. We believe that the analysis is at the limit of tractability, and could best be pursued by computer simulation techniques of the types discussed in Section II B. We do not propose to continue along such lines in the 1974-5 funding period.

As an essential element in our VLF emission studies, tedious numerical studies of whistler dispersion relations were required. These and other instability problems involving the wellknown Fried function can be greatly simplified if good approximations to this function are available. Such approximations were developed in the course of our work, and have been published recently to complete the project.[2]

---

* References 1-20 are to be found in Section IV. The remainder are given in Section V.

Alfvén Wave Excitation: A variety of mechanisms have been suggested for the origin of Pc 1 emissions in the ionosphere. We have considered in detail the possibility that they might be generated as Alfvén waves by the nonlinear interaction of two relatively high frequency whistlers. In particular, we have demonstrated that magnetic field strengths of the order of 40 mγ might be generated, which is of the appropriate order for Pc 1 emissions. The work has been written up, presented at a conference,[8] and published recently.[12] No further extensions are intended.

Briefly, the interaction occurs for waves whose propagation vectors must not all be collinear with the earth's magnetic field. One of the conditions in our theory for the instability requires that the whistlers be at frequencies at which their group velocity is approximately the Alfvén speed, i.e. $\omega \approx 0.95\, \omega_{ce}$. Superficially, it would appear that this could not be attained in practice, since whistlers are ducted only for $\omega < 0.5\, \omega_{ce}$. Recent experimental evidence suggests, however, that whistlers approach the electron gyrofrequency resonance after they become unducted. Since a resonance is associated with zero group velocity, the ratio ω/ω_{ce} must pass through the range of values between about 0.5 and 1.0 along that portion of the trajectory between the commencement of nonducting and resonance. At some point in the trajectory, therefore, the condition where the group velocity equals the Alfvén velocity will be met.

Consideration has been given to the effects of collisions, and parametric amplification, on the process. In the magnetosphere, the only important collision process is between electrons and ions, the density of neutrals being negligible. Our analysis has shown that the decay distance due to collisions is much greater than the width of the interaction region, i.e. collisions will have little effect. We have shown that the threshold for parametric amplification is exceeded over most of the interaction region. The interaction region is too narrow, however, for parametric effects to be felt. We have demonstrated this by showing for a typical case that the whistler, acting as the signal wave, grows by only 5% across the interaction region, an amount which is small enough to allow us to disregard any parametric back-reaction on the Alfvén wave.

VLF Antennas: A new method of generating VLF signals has been proposed recently in which helical electron beams, fired from satellites, are to be used to radiate whistlers.[29] The satellites are assumed to be instantaneously on the L = 4 shell at an altitude of 500 km. Electron beams of about 1A and 10 keV energy are to be injected from 20 satellite-mounted guns in a circular array of the order of 100 meters in diameter. The frequencies and amplitudes of the radiated whistlers will depend on the pulse frequency, and angle at which the beam is injected into the earth's magnetic field. It has been claimed that the total power radiated from such a set-up will be at least a few tens of watts, and that the power flux will be of the order of 10^{-4} W/m^2 . This is greater than that achievable by ground-based VLF transmitters by a factor of 10^6.

We have been considering the new proposal carefully, and trying to determine the feasibility of carrying it out as part of the PPEPL project. We note that the proposer of the idea had neglected to consider the stability of the beam to longitudinal wave growth. According to rough calculations of the growth rate of longitudinal instabilities, due to beam-plasma interaction,[30] we believe that the beam cannot travel far before its helical structure and phase coherence are broken up by such instabilities. In the cold beam approximation, the time needed for the instabilities to grow from thermal noise to the energy level of the beam is of the order of 10^{-7} sec. To be conservative, we take 10^{-6} sec as the life-time of the helix. The calculated radiation power from the beam then turns out to be three to five orders of magnitude lower than had been claimed. In addition, effects due to collisions still remain to be taken into account. We are currently investigating the problem in more detail, and trying to establish the feasibility of this method of generating whistlers, as compared to that of a conventional metal VLF antenna trailing behind the PPEPL. Some further comments on our program of work on beam-plasma interactions are given in Section II C.

ULF Antennas: Above, we have discussed the possibility of exciting Alfvén waves by nonlinear interaction of whistlers. During the last few months, we have also considered the rather more mundane case of ULF excitation by metallic electric or magnetic dipole antennas. The project was transferred to this grant after other sponsorship ended, and was rapidly brought to a successful conclusion. In particular, the field strengths generated in the ionosphere were determined for a general direction of the earth's magnetic field, and taking into account the dielectric properties of both the earth above which the antenna was assumed to be suspended, and the free space region below the ionosphere. The work has been written up in report form,[13] and will be submitted for publication soon. No further studies of this method of ULF excitation are envisaged: we prefer to concentrate on the electron-beam excitation method described in the previous subsection for VLF waves.

B. Computer Simulation

We remarked in Section II A that the analysis of triggered VLF emissions has been carried to the limit of tractability, and that further progress can probably be made most effectively by use of computer simulation techniques. Such techniques are of potential use in a wide variety of significant problems, particularly involving plasma inhomogeneity and nonlinear wave-particle interactions. In entering this area, it was logical to begin with the onset phase of triggered VLF emissions, which we had previously analyzed approximately,[27] before proceeding to the more complicated phase of evolution of the wave-packet in an inhomogeneous magnetoplasma. For simplicity, however, we preferred to begin not by considering the nonlinear behavior of a large-amplitude whistler, but to develop and test appropriate simulation techniques on the easier and very basic case of a large-amplitude electron plasma wave, which we had also previously analyzed approximately as part of our work under this grant.[31]

Plasma simulation on the computer entrains many problems of its own, in particular those of expense if a large number of charged particles are to be followed, and unwanted fluctuations if the number of particles is small. To avoid them, we have applied a hybrid method originally proposed by Denavit,[32] for effectively collisionless plasmas, which provides a virtually noise-free plasma. This method enables us to perform simulations at signal amplitudes small enough to satisfy the assumptions made in the theory; the usual particle simulation codes are too noisy to allow that. The total number of electrons used is typically 16384; ions are treated as smeared-out background positive charge; there are usually 256 spatial grid points in the system, which is 256 electronic Debye lengths long, and 64 velocity grid points in the velocity interval of $-4.5\ v_t < v < 4.5\ v_t$, where v_t is the electron thermal velocity.

During the past few months, our simulation studies have been written up in a comprehensive Ph.D. thesis by Y. Matsuda.[11] This first reviews and compares a wide variety of conventional simulation techniques, and then demonstrates the extraordinary effectiveness of the hybrid method: noise can be reduced by six orders of magnitude at computational costs within about a factor of two of previous methods. As an example, linear Landau damping is studied numerically at a ratio of wave energy/plasma thermal energy four orders lower than in any previous work known to us.

The thesis then compares the behavior of a large-amplitude wave with previous theories. The essence of these theories is that the large-amplitude wave distorts the time-averaged electron velocity distribution into double-humped form, which is unstable to sideband growth near the phase velocity of the large amplitude wave. In practice, sidebands would grow from noise. In our simulations, a small-amplitude test wave was injected, and its growth rate was measured. So far, we have found that the time evolution of the distortion of the spatially averaged distribution function agrees with the analytical result, and that the distortion of the averaged distribution function is responsible for the behavior of the sideband wave, as predicted by theory.[31]

In addition to the sideband growth, additional satellite frequencies are generated involving other sidebands and the second harmonic of the large-amplitude wave.[5] A plausible four-wave interaction mechanism intended to explain this was examined, but proved inadequate to account for the amplitude of the satellite.[6] A new mechanism was then considered, involving modulation of the large amplitude wave. This proved highly successful in predicting the satellite amplitude.

Two manuscripts on the simulation work are in preparation, and will be submitted for publication soon. The first of these will deal with the hybrid simulation method, treating both linear and nonlinear Landau damping as examples. The second will treat sideband and satellite growth. The development of simulation techniques will then be considered as completed. It is not our intention to return to the simulation of triggered VLF emissions during the coming year, but rather to use the techniques on other problems, particularly associated with the nonlinear velocity spreading of charged particle beams due to beam-plasma interaction This will be discussed in Section II C.

C. Beam-plasma Interaction

Two aspects of beam-plasma interaction have been of interest to us during the last twelve months: first, the beam velocity spreading caused by wave growth from noise to large amplitude, and second, the possibility of low group velocity wave propagation in the linear régime. The beam spreading phenomenon is relevant to proposed beam injection experiments, involving for example VLF excitation or field line tracing; low group velocity propagation is relevant to long delayed radio echoes (LDE).

Beam Velocity Spreading: It is likely that many experiments associated with the PPEPL will involve injection of electron or ion beams into the ionosphere. We have already mentioned in Section II A the proposal that helical electron beams might function as VLF antennas.[29] Other suggestions involve magnetic field line tracing, excitation of artificial auroras, and stimulated precipitation of trapped particles. Now, it is wellknown that beam-plasma instability is a powerful wave growth mechanism, and it is important to establish what influence this phenomenon is likely to have on beam injection experiments. The empirical evidence is that, even under conditions where beam-plasma interaction may be expected to grossly distort the beam electron velocity distribution before it leaves the vicinity of the vehicle, the beam reaches points far remote from the vehicle.[33] The implication is that though beam velocity spreading may occur, the mean velocity is (roughly) maintained.

This would have a serious effect on experiments in which high coherence is required, e.g. for VLF antennas, but less significance in field line tracing and production of artificial auroras.

We have been applying previous work on beam-plasma interactions, carried out at Stanford and elsewhere, to establish typical growth rates for likely beam and ionospheric parameters. We have begun by studying a cold, bounded beam in a cold, unbounded magnetoplasma. This should provide an upper limit on the growth rate. The studies are currently being extended to a warm beam in a warm background plasma. It is anitcipated that this work will continue during the renewal period, and be pursued to the nonlinear limit, in which beam velocity spreading occurs, using the efficient computer simulation techniques referred to in Section II B.

Low Group Velocity Propagation: For the last five years, an ionospheric sounding program has been proceeding at Stanford to determine whether a curious phenomenon reported by van der Pol and Stormer in 1928 really exists or not, and if so to determine its origin. The effect is simply that radio signals, e.g. Morse dashes, can apparently return from the ionosphere with tens of seconds delay. Sporadic observations by a large number of amateurs lend credence to the idea that the effect is genuine, but no systematic studies have been unequivocally successful. Some suggestive echo data from the Stanford experiments have led to a theory of the phenomenon based on beam-plasma interaction due to precipitating fast particles interacting with the ionosphere so as to allow low group velocity propagation (hence long delay) without undue collisional attenuation.[34]

Recently, NSF support for the LDE program came to an end, and was replaced by support from this NASA grant. The observational program has not been continued, but we have strong reasons for pursuing the theoretical work: first, our most recent numerical results show very encouraging agreement with the observed characteristics of LDE,[17] and second, the PPEPL offers the possibility of studying the phenomenon from the topside of the ionosphere. We shall look into the feasibility of doing so as part of our program during the next reporting period.

D. Low-frequency Instabilities

For several years, we have been studying a variety of mechanisms of low-frequency instability in laboratory and space plasmas. These have been examined in relation to the ionospheric phenomenon of spread-F (which now seems likely to be due to an electron temperature gradient-induced instability), to the positive column, and to the hollow cathode arc discharge. The last was imposed upon us as part of our studies of whistler propagation in the laboratory: our efforts to verify the plane wave whistler dispersion relation in a collisional plasma wave had been highly successful,[21,22] but attempts to extend the work to plasma conditions where the collisionless cyclotron damping due to electron thermal velocities exceeds the damping due to Coulomb and electron-neutral collisions were not; the hollow-cathode arc discharge used for the experiments was the source of low-frequency instabilities which precluded precise experimentation on whistlers Our studies of these instabilities have been published during the current year,[1,3] together with some relevant theory of the steady state, non-isothermal, positive column.[4] Since an experimental verification of collisionless electron cyclotron damping performed elsewhere has been reported recently,[35] and Dr. Rognlien is now continuing his studies relating low-frequency instabilities to spread-F at the NOAA in Boulder, Colorado, we do not plan to extend the project further at Stanford.

E. Nonlinear Scattering from the Ionosphere

With the successful verification in space and laboratory plasmas of predicted properties of cold and warm plasma waves, attention has become focused in recent years on nonlinear wave-wave and wave-particle interactions. Our effort has been given to three practical problems; incoherent backscatter, ionospheric heating, and (possible) nonlinear scattering from meteor trails, and a general theoretical analysis, using Lagrangian methods, to be described in Section II F.

Incoherent Backscatter: Over the last few years, radar backscatter from the ionosphere has become a prime diagnostic technique for obtaining the ionospheric electron density and temperature profiles, and measuring charged particle drifts. The relevant theories were developed before considerable attention was given to wave-wave interactions in plasma, and do not clarify the nature of the scattering in terms of three-wave coupling. During the last year or so, we have been re-examining the analysis to provide a new derivation putting the wave-wave interactions more clearly in evidence, and have obtained some correction factors to commonly used scattering coefficients which may be significant under practical conditions in space or laboratory plasmas. The work has been written up for publication and is considered to be completed.[7,18]

Ionospheric Heating: There is now ample evidence that the ESSA high-power (~ 1 MW) sounder at Boulder can produce nonlinear wave phenomena in the ionosphere, including anomalous absorption.[36,37,16] Under such conditions, when a high-intensity signal propagates through the ionosphere, three separate nonlinear mechanisms can operate to increase the "resistive" losses above those due simply to the collisional effects included in linear theory. The mechanisms are:[38-42] (a) thermal instability, (b) oscillating two-stream instability, and (c) parametric instability. The coupled-mode formalism that we have used in our wave-wave analyses under this grant provides a suitable approach to the last two mechanisms. Both of them depend on the nonlinear interaction between ordinary, Langmuir, and ion-acoustic waves.[43,44]

Such instabilities can be, and have been, studied by the radar backscatter technique. This raises an important question which was studied as part of our program last year: even though the heating signal may be effectively monochromatic, Langmuir and ion acoustic waves will be excited over a band of frequencies; what will be the shape of the backscattered spectrum? This involves taking account of the nonlinear saturation mechanisms which limit the parametric growth. Our work on this problem was submitted for publication last year.[45] In response to comments by the reviewer, the analysis has been modified during recent months, and a revised version is to be submitted to the journal shortly. The project will not be pursued further.

Meteor Trails: A few years ago, what appeared to be nonlinear scattering from meteor trails was reported.[46] The problem was studied theoretically and experimentally as part of our program under the grant,[47-51] and it was concluded that the scattering is far too weak to account for the results of Ref. 46, which seem to be spurious. A final manuscript on the work is in preparation, and should be submitted for publication within the next few months. No further extension of the project is planned.

F. Lagrangian Formalism

The analysis of nonlinear wave-wave and wave-particle interactions usually leads to extremely tedious algebra. It is consequently highly desirable to have a compact and efficient formalism for obtaining such quantities as wave coupling and parametric growth coefficients. Such a formalism has been developed at Stanford over the last three or four years with partial support from this NASA grant. It involves a perturbation expansion of a Lagrangian density characterizing the plasma, which may be described by Vlasov, macroscopic, or cold plasma theory. The work has been described in detail in three Ph.D. theses, one of which has been completed very recently.[52,53,14] Our previous work,[52,53] covered coherent wave-wave interactions in cold and Vlasov plasmas, and considered some extensions to describe wave-particle interactions. The latest work[14] concentrates on the macroscopic Lagrangian, and its applications to nonlinear wave-wave interactions and to linear resonances in inhomogeneous plasmas. No further work on the formalism is envisaged, but it is expected that a number of manuscripts on the work already completed will be prepared during the next few months, and submitted for publication.

Macroscopic Lagrangian: The main contributions of the thesis are as follows. The general inverse problem of the calculus of variations is first studied, i.e. the method required to derive an appropriate Lagrangian from a given set of differential equations is examined with the plasma moment equations in mind. Although useful contributions to this area are made, involving the inclusion of dissipative effects, it seems to be more satisfactory in practice to deduce an appropriate macroscopic plasma Lagrangian from energy considerations. This is done, together with derivation of the corresponding Hamiltonian. Applications to a variety of wave-wave interactions involving whistlers, electron plasma waves, and ion acoustic waves are next examined in detail, and the predicted effects are compared to results of relevant experiments performed elsewhere, taking collisional effects into account.

It is anticipated that separate papers will be written on the inverse problem, derivation of the Lagrangian, and the applications to wave-wave interactions experiments. A brief note on the microscopic Hamiltonian has already been written.[15]

Inhomogeneous Plasma Resonances: As an illustration of how the use of the macroscopic plasma Lagrangian can greatly simplify complex problems of practical significance in laboratory and space plasmas, we have studied the classic case of the warm plasma resonances of an inhomogeneous plasma column, for which 'exact' solutions were computed, using a macroscopic plasma model, some ten years ago by Parker *et al*.[54] The work has been written up in report form, and submitted for publication.[10]

Previous theoretical treatments of the electron resonance problem have given predictions which agree well with experimental data.[54,55] However, they were limited either to a ratio of (column radius/Debye length) ≤ 70, when the approach involved direct numerical solution of the relevant differential equations,[54] or to treatment only of higher order resonances, when the approach involved joining of inner-outer expansion approximations.[55] We have taken a variational approach which is applicable over the entire range of ratios of (column radius/Debye length). The associated numerical method mainly involves evaluations of integrals, and gives the first few resonance solutions quickly and accurately.

The Rayleigh-Ritz procedure that we have used has been extensively applied to single self-adjoint equations.[56] It was used in terms of a single Euler-Lagrange equation for a cold nonuniform plasma column, by Crawford and Kino,[57] and by Dorman[55] for a one-dimensional warm plasma slab. For more complicated warm inhomogeneous cylindrical plasmas, reduction of the equations to a single higher order Euler-Lagrange equation is often difficult. We have been able to establish a macroscopic Lagrangian which provides a system of three Euler-Lagrange equations, and to develop the Rayleigh-Ritz method for this system of Euler-Lagrange equations. Despite the fact that the equations are not elliptic, we have found that accurate resonance frequencies can be predicted, provided that a restricted set of coordinate functions is used. The resonance frequencies calculated with this method agree very closely with those of Parker _et al_.[54]

G. Pulse Propagation

Although the propagation of continuous waves through essentially homogeneous plasmas has been studied for over forty years, it is only in the last decade that transient propagation has received much attention. Under this grant, we have already conducted some pulsed propagation studies of cyclotron harmonic waves,[59] and obtained sufficiently good agreement with the theoretical dispersion characteristics for the group delay to be used as a non-perturbing plasma diagnostic technique. With the PPEPL, the opportunity is offered of carrying out such experiments under conditions where instrumentation problems are very much simpler to solve than in the laboratory. It is our intention to examine the range of possible experiments. To begin with cold plasma propagation, packets in the ordinary and extraordinary modes could be excited with effectively delta-function pulses ($\sim$ 10 ns), and exhibit the features predicted by Brillouin and Sommerfeld around WW I.[60] These still await detailed verification with respect to such phenomena as "forerunners". Warm plasma wave propagation in the Landau and cyclotron harmonic modes could also be studied.

During the last twelve months, we have been analyzing the wave-packets produced by delta-function excitation of a cold magnetoplasma. This should give two branches of right-hand polarized propagation, and one left-hand polarized branch, for wavevectors parallel to the earth's magnetic field. The analytical results are now being studied numerically. Extensions to this project are expected to form a significant part of our program during the coming reporting period.

III. FUTURE RESEARCH PROGRAM

As remarked in Section I, over the last eighteen months six Ph.D. theses receiving support from this grant have been completed. This has given us the opportunity of reorienting a significant fraction of the program. We have chosen to do so in the direction of the new generation of plasma experiments facilitated by the proposed PPEPL; those projects to be mentioned below are aimed either at developing basic plasma experiments to be carried out most profitably with that vehicle, or at refining diagnostic techniques for measuring ionospheric characteristics near to, or remote from it. Some of the elements contained in our projects have already been tentatively proposed for the PPEPL by ourselves and many others. It is hoped that the new information to be gained from our proposed program will help materially in assessing the feasibility and potential scientific rewards to be gained from including them in the PPEPL program. As in the past, our work will rely on theoretical analysis, together with laboratory experimentation where significant advances can be made by suitable scaling of space plasma parameters.

Of those projects described in Section II A, under whistlers, only that on VLF excitation by an electron beam will be continued; those on triggered VLF emissions, nonlinear generation of Alfvén waves, and ULF generation by metallic antennas, are regarded as completed. The computer simulation techniques described in Section II B are now available for use, particularly in relation to the beam velocity spreading phenomena of Section II C, and they will only be extended as necessary during the coming year. The remaining beam-plasma interaction phenomenon from Section II C, that of low group velocity propagation, will be followed up in connection with the LDE experiment on the topside ionosphere. The low-frequency instability projects of Section II D, the nonlinear ionospheric scattering projects of Section II E, and the Lagrangian formalism projects of Section II F, will not be pursued further, after submission or publication of the manuscripts mentioned in those sections has occurred. We wish to continue the pulsed propagation studies mentioned in Section II G, however. Some additional work, involving basic plasma phenomena and potential diagnostic techniques which have not formed part of the program for the 1973-4 year, will be undertaken on cyclotron harmonic wave phenomena and the resonance cone. In summary, then, the topics for the next reporting period will be:

(1) VLF Excitation by Electron Beams

(2) Beam Velocity Spreading

(3) Long Delayed Echoes (LDE)

(4) Pulse Propagation

(5) Cyclotron Harmonic Waves (CHW)

(6) Resonance Cone

IV. REPORTS, CONFERENCE PAPERS, AND PUBLICATIONS RESULTING FROM NASA GRANT NGL 05-020-176 (1 July 1973 - 30 June 1974)

1. Ilić, D. B., Rognlien, T. D., Self, S. A. and Crawford, F. W., "Low-Frequency Flute Instabilities of a Hollow Cathode Arc Discharge: Theory and Experiment"
   Phys. Fluids 16, 1042 (July 1973).

2. Brinca, A. L., "Approximations to the Plasma Dispersion Function"
   J. Plasma Phys. 10, 123 (August 1973).

3. Rognlien, T. D., "Low-frequency Flute Instabilities of a Bounded Plasma Column"
   IPR No. 540 (August 1973)
   J. Appl. Phys. 44, 3505 (August 1973)

4. Ilić, D. B., "Theory of a Steady-State Non-Isothermal Positive Column in a Magnetic Field"
   J. Appl. Phys. 44, 3993 (September 1973).

5. Matsuda, Y., Crawford, F. W. and Self, S. A., "Computer Simulation of Nonlinear Process in a Two-Wave System"
   *Proc. XIth International Conference on Phenomena in Ionized Gases, Prague, Czechoslovakia, September 1973 (Czechoslovak Academy of Sciences, Prague, 1973), p. 340.

6. Brinca, A. L., "Sideband Growth and Macroscopic Four-Wave Interaction"
   *Proc. XIth International Conference on Phenomena in Ionized Gases, Prague, Czechoslovakia, September 1973 (Czechoslovak Academy of Sciences, Prague, 1973), p. 341.

7. Harker, K. J. and Crawford, F. W., "Theory for Incoherent Scatter Based on Three-Wave Interaction"
   *Proc. XIth International Conference on Phenomena in Ionized Gases, Prague, Czechoslovakia, September 1973 (Czechoslovak Academy of Sciences, Prague, 1973), p. 359.

8. Harker, K. J., Crawford, F. W., and Fraser-Smith, A. C., "Generation of Alfven Waves in the Magnetosphere by Parametric Interaction between Whistlers"
   *15th Annual Meeting of Plasma Physics Division of American Physical Society, Philadelphia, Pennsylvania, October 1973
   Bull. Am. Phys. Soc. 18, 1267 (October 1973) [Abstract only].

IPR = Stanford University Institute for Plasma Research Report.
 * = Conference presentation

9. Brinca, A. L., "Whistler Triggered Emissions"
*AGARD Meeting on Nonlinear Effects in Electromagnetic Wave Propagation, Edinburgh, Scotland, November 1973.

10. Peng, Y. M. and Crawford, F. W., "Variational Calculations for Resonance Oscillations of Inhomogeneous Plasmas"
IPR No. 548 (November 1973).
J. Plasma Phys. (submitted for publication).

11. Matsuda, Y., "Computational Study of Nonlinear Plasma Waves"
IPR No. 567 (March 1974) [Ph.D. Thesis].

12. Harker, K. J., Crawford, F. W. and Fraser-Smith, A. C., "Generation of Alfven Waves in the Magnetosphere by Parametric Interaction between Whistlers"
J. Geophys. Res. 79, 1836 (May 1974).

13. Harker, K. J., "Generation of ULF Waves by Electric or Magnetic Dipoles"
IPR No. 577 (May 1974).

14. Peng, Y. M., "A Macroscopic Plasma Lagrangian and Its Application to Wave Interactions and Resonances"
IPR No. 575 (June 1974) [Ph.D. Thesis].

15. Peng, Y. M., "Microscopic Plasma Hamiltonian"
IPR No. 576 (June 1974).

16. Crawford, F. W., "Heating Experiments in the Ionosphere"
*Proc. APS/IEEE Second Topical Conference on RF Plasma Heating, Lubbock, Texas, June 1974 [Invited paper] (to be published).
IPR No. 578 (June 1974).

17. Crawford, F. W., and Sears, D. M., "Experimental Observations and a Proposed Explanation of Very Long Delayed Echoes from the Ionosphere"
*Second European Conference on Cosmic Plasma Physics, Oxford, England, July 1974 (to be presented).

18. Harker, K. J. and Crawford, F. W., "A Theory for Scattering by Density Fluctuations Based on Three-Wave Interaction"
J. Plasma Phys. 11, 435 (1974).

Semiannual Reports

19. No. 13 (1 January - 30 June 1973)
IPR No. 536 (July 1973).

20. No. 14 (1 July - 31 December 1973)
IPR No. 560 (January 1974).

V. REFERENCES

21. Lee, J. C., Stanford University Institute for Plasma Research Report No. 312 (May 1969) [Ph.D. Thesis].

22. Lee, J. C., Fessenden, T. J., and Crawford, F. W., Proc. IXth International Conference on Phenomena in Ionized Gases, Bucharest, Rumania, September 1969, p. 475.

23. Crawford, F. W. and Lee, J. C., Published in Plasma Waves in Space and in the Laboratory. Eds. J. O. Thomas and B. J. Landmark (Edinburgh Univ. Press, Edinburgh, 1970), Vol. 2, p. 447.

24. Lee, J. C. and Crawford, F. W., J. Geophys. Res. 75, 85 (1970).

25. Brinca, A. L., J. Geophys. Res. 77, 3495 (1972).

26. Brinca, A. L., Stanford University Institute for Plasma Research Report No. 489 (October 1972) [Ph.D. Thesis].

27. Brinca, A. L., J. Geophys. Res. 77, 3508 (1972).

28. Brinca, A. L., J. Geophys. Res. 78, 181 (1973).

29. Dowden, R. L., J. Geophys. Res. 78, 684 (1973).

30. Self, S. A., Shoucri, M. M., and Crawford, F. W., J. Appl. Phys. 43, 704 (1971).

31. Brinca, A. L., J. Plasma Phys., 7, 385 (1972).

32. Denavit, J., J. Comp. Phys. 9, 75 (1972).

33. Hess, W. N., Trichel, M. C., Davis, T. N., Beggs, W. C., Kraft, G. E., Stassinopoulos, E., and Maier, E. J. R., J. Geophys. Res. 76, 6067 (1971).

34. Crawford, F. W., Sears, D. M., and Bruce, R. L., J. Geophys. Res. 75, 7326 (1970).

35. McVey, B. D., and Scharer, J. E., Phys. Fluids 17, 142 (1974).

36. Utlaut, W. F., J. Geophys. Res. 75, 6402 (1970).

37. Utlaut, W. F., Violette, E. J., and Paul, A. K., J. Geophys. Res. 75, 6429 (1970).

38. Kaw, P. K. and Dawson, J. M., Phys. Fluids 12, 2586 (1969).

39. Sanmartin, J. R., Phys. Fluids 13, 1533 (1970).

40. Nishikawa, K., J. Phys. Soc. Japan 24, 916 and 1152 (1968).

41. DuBois, D. F. and Goldman, M. V., Phys. Rev. 164, 207 (1967).

42. Goldman, M. V., Ann. Phys. 38, 95 (1966).

43. Harker, K. J., Proc. Xth International Conference on Phenomena in Ionized Gases, Oxford, England, September 1971 (Donald Parsons, Oxford, 1971), p. 360.

44. Harker, K. J., Int. J. Elect. 32, 297 (March 1972).

45. Kim, H., Stanford University Institute for Plasma Research Report No. 509 (March 1973).

46. Green, J. A., J. Geophys. Res. 70, 3244 (1965).

47. Bruce, R. L., Crawford, F. W., and Harker, K. J., Proc. Third International Conference on Quiescent Plasmas, Elsinore, Denmark, September 1971: Published as Danish Atomic Energy Commission Risö Report No. 250 (October 1971), p. 349.

48. Bruce, R. L., Crawford, F. W., and Harker, K. J., Proc. Xth International Conference on Phenomena in Ionized Gases, Oxford, England, September 1971 (Donald Parsons, Oxford, 1971), p. 326.

49. Bruce, R. L., Crawford, F. W., and Harker, K. J., Bull. Am. Phys. Soc. 16, 1273 (November 1971).

50. Larsen, J. M., Stanford University Institute for Plasma Research Report No. 493 (October 1972) [Ph.D. Thesis].

51. Larsen, J. M., J. Appl. Phys. (in press).

52. Kim, H., Stanford University Institute for Plasma Research Report No. 470 (May 1972) [Ph.D. Thesis].

53. Galloway, J. J., Stanford University Institute for Plasma Research Report No. 488 (October 1972) [Ph.D. Thesis].

54. Parker, J. V., Nickel, J. C., and Gould, R. W., Phys. Fluids 7, 1489 (1964).

55. Baldwin, D. E., Phys. Fluids 12, 279 (1969).

56. Mikhlin, S. G., Variational Methods in Mathematical Physics, (Pergamon, New York, N. Y., 1964).

57. Crawford, F. W., and Kino, G. S., C. R. Acad. Sc. 256, 1939 and 2798 (1963).

58. Dorman, G., J. Plasma Phys. 3, 387 (1969).

59. Crawford, F. W., Harp, R. S., and Mantei, T. D., J. Geophys. Res. 72, 57 (1967).

60. Brillouin, L., Wave Propagation and Group Velocity (Academic Press, New York, N. Y., 1960).